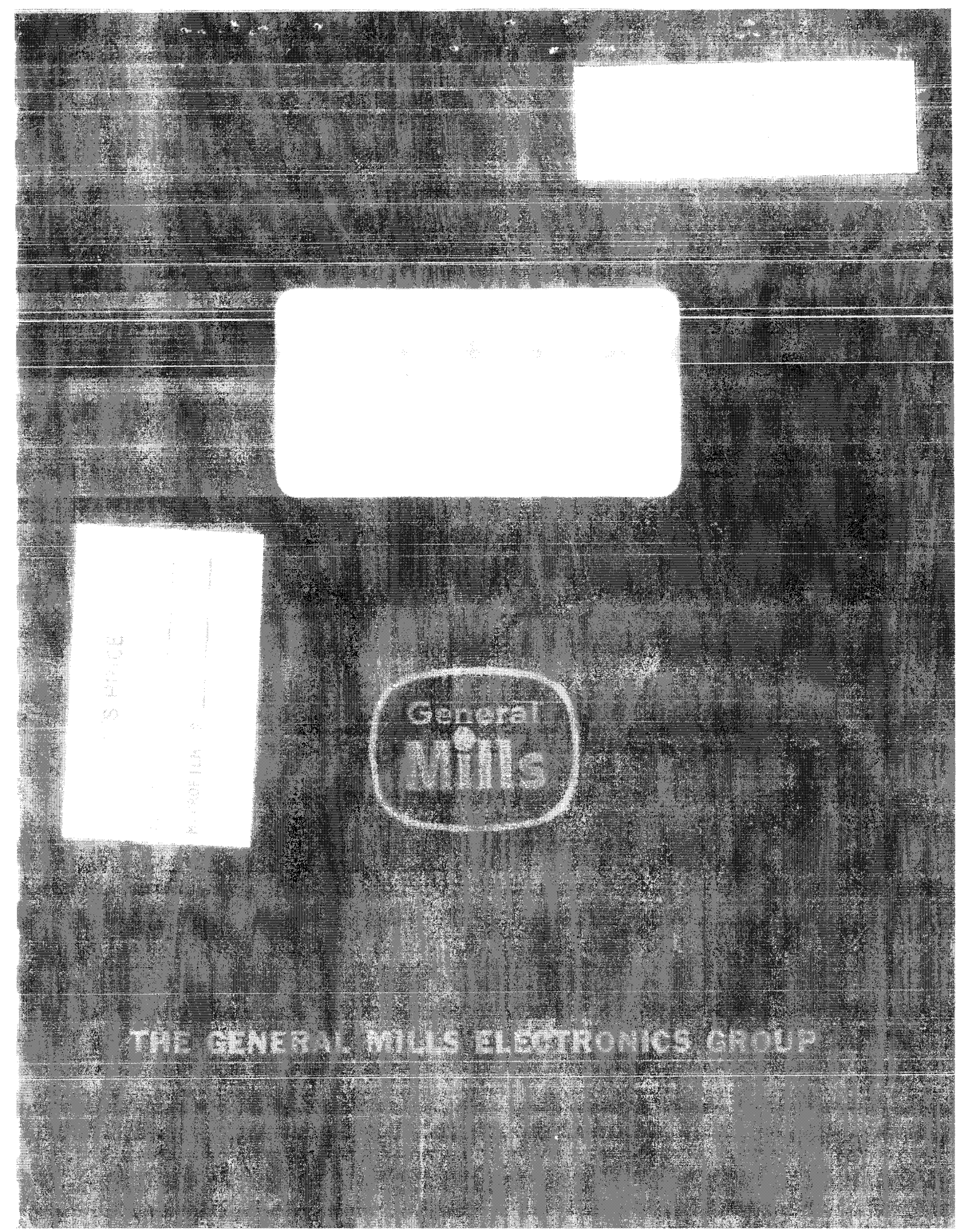
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UNCLASSIFIED

INVESTIGATION OF SPUTTERING EFFECTS ON THE MOON'S SURFACE

First Quarterly Status Report,
(NASA Contract NASw-751; Proj. 89308)
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First Quarterly Status Report
Contract NASw-751

INTRODUCTION

This contract is a continuation of previous Contract NASw-424. The major results obtained under the previous contract have been summarized in a paper "Sputtering Rates Under Solar-Wind Bombardment" which is scheduled to appear soon in "Planetary and Space Science".

Further results partly obtained under the previous contract and in the first quarter of the present contract have been summarized in a paper "Modification of the Lunar Surface by the Solar-Wind Bombardment" which has been accepted for publication in "Planetary and Space Science". We hereby submit this paper as our first quarterly report.

Results obtained thus far were presented at the "Lunar Surface Materials Conference" 22 May 1963 in Boston, Massachusetts, and will appear in printed form in the Conference Proceedings.

In our extension of the program we have (1) continued to survey the literature for improved solar-wind and micrometeorite-impact data, (2) studied more closely the composition changes in ion-bombarded surfaces with x-rays, (3) measured the influence of the angle of incidence of 6-kev H_3^+ beams on sputtering yields, and (4) started to investigate the photometric properties of ion-bombarded surfaces. These studies will be described in the next quarterly report.

Modification of the Lunar Surface by the Solar-Wind Bombardment*

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ABSTRACT

Long-duration, solar-wind sputtering conditions were simulated at a much accelerated scale with mass-separated hydrogen ion beams or in low-pressure, noble-gas or hydrogen plasmas. Experiments with metal targets and metal-, oxide-, and rock-powder samples demonstrate the leveling and smoothing of macroscopic surface features, and cementing together of loose particles into a porous, brittle, fibrous crust. Certain oxide surfaces become enriched with metal atoms under the bombardment and sputtering action. It is concluded that many of the unusual properties of the lunar surface can be explained by the action of solar-wind bombardment.

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I. INTRODUCTION

By simulating solar-wind conditions in the laboratory, we were able to give fairly reliable estimates of the sputtering rates for an unprotected body like the Moon[1] in orbit around the Sun. These rates are small, but not negligible, for long bombardment times. We obtained, for a proton flux of $2 \times 10^8/cm^2$ sec and a superimposed α-particle flux of $0.3 \times 10^8/cm^2$ sec at 600 km/sec particle velocity, rates of ~ 0.3 Å/year for Fe, and 0.4 Å/year for stony materials. In agreement with previous estimates by Reiffel[2] it appears that the He component in the solar wind is more important to sputtering than the proton component. If the solar wind blew with the same intensity over the period of the Moon's existence, one finds that the Moon must have lost a layer of roughly 20 cm thickness in 4.5×10^9 years. This is of the same order as estimated for the accretion of micrometeoric material.[3] From measurements of the velocity distribution of sputtered atoms, we conclude that many of the sputtered atoms have velocities which are higher than the escape velocity of the Moon.[1]

In the course of those sputtering measurements in which we have simulated solar-wind conditions with mass-separated, hydrogen-ion beams or in low-pressure, noble-gas or hydrogen plasmas, a variety of observations with regard to modifications of the bombarded target surfaces were made. From these, one can draw some interesting conclusions as to structural and compositional changes which must have taken place over the millenia on the lunar surface.

II. EXPERIMENTS

When material is sputtered from a polished metal surface, the target becomes rough on a microscopic scale because differently oriented crystallites are sputtered at different rates and grain boundaries as disturbed regions usually appear as furrows. Further, the surface becomes covered with etch pits, but these cannot be correlated with the original dislocations in the lattice.[4] Obviously the bombardment causes considerable rearranging of single dislocations in the region close to the surface. Imbedded insulating or low-sputtering rate particles can shadow the material underneath and

leave hillocks or spires which extend up to the height of the original surface. Occasionally protrusions or spires are found which extend above the original surface. These probably grew from surface-migrated or sputtered-and-reattached atoms.

A macroscopically rough surface becomes smoother under sputtering action because many atoms are dislodged and transported to the deeper lying areas of the target surface. This happens because atoms sputtered from a flat surface by obliquely incident ions are preferentially ejected in a forward direction. Material sputtered from the flanks and sides of protrusions on a rough surface is therefore pushed into holes and crevices. This phenomenon was demonstrated by sputtering a metal screw in a low-pressure plasma.[1] The threads are seen to become more and more shallow as sputtering proceeds.

a. Experiments With an Assembly of Small Steel Balls

A number of interesting phenomena can be demonstrated when one bombards and sputters a dish filled

with small, closely packed metal spheres. We performed such experiments with 0.75-mm diameter steel balls in a low-pressure, Hg plasma. The Hg plasma was created in a grid-stabilized, dc vacuum arc between a Hg-pool cathode and an anode, in the geometry of much of our previous sputtering work.[5] The discharge data were: arc current, 4 amp; arc voltage, ~ 25 volts; Hg gas pressure, 1 torr; target at minus 500 volts with respect to plasma; ion current density at target, ~ 10 ma/cm^2; thickness of ion sheath covering the target, several mm; under the bombardment the target assumes a temperature of ~ 300°C. Compared to the solar wind, one has here a much higher flux density and a much higher sputtering yield. In fact, an estimate shows that one hour of laboratory sputtering under these conditions should be equivalent to several million years of solar-wind sputtering at the lunar surface.

Figures 1 to 4 show various stages of progress in sputtering this sphere assembly. The observations can be summarized as follows:

1. With the ion-accelerating sheath larger than

the sphere diameters, the surface plane is essentially under normal incident bombardment. Individual spheres experience normal ion incidence at the leading top area, but oblique incidence at the sides. Sputtering rates under oblique incidence are higher than under normal incidence and for this reason the surface spheres assume a conical shape (see Fig. 2), as previously observed with single Fe or Mo spheres sputtered in a uniform ion beam.[6]

2. The ions are able to enter into the assembly more deeply at places where the top layer leaves holes between touching spheres. The lower spheres are then sputtered in areas which are sharply defined by the "masking" of the upper spheres. Such spheres are photographed in Fig. 5.

3. Many sputtered atoms are ejected in a forward direction and pushed deeper into the assembly of spheres. These atoms build up deposits which contribute not only to the leveling of the surface, but which at the same time provide the "cement" to seal touching spheres together. A layer of spheres containing spheres from the second and even the third layer can then be lifted off as a crust after the target has been sputtered for a sufficiently long time (Fig. 6).

4. After the top layer of spheres has been sputtered off completely, which in our experiments took about 100 hours, flaky, porous deposits appear at places between the spheres. They look like a dark mold (Fig. 3 and 4) but when illuminated and viewed from the side they turn out to be shiny, closely spaced spires and flakes with a metallic appearance. They probably originate from flakes and remnants sputtered free and aligned, normal to the target surface, by the electric field and the bombardment. The fact that this "mold" stands out from the surface indicates that this configuration must have a low-sputtering yield. This is not surprising because high surface roughness favors the recapture of sputtered atoms.

b. Experiments With Metal Powders

In sputtering of metal dust under similar discharge conditions, the following observations were made:

1. The metal dust (Fe or Mo) has originally a dull, greyish appearance. The surface assumes a shiny metallic appearance after sputtering. Oxide films are

obviously removed and the exposed surfaces are becoming atomically clean.

2. A brittle crust is formed after more than 40 coul/cm^2 of sputtering. This crust can be lifted off in pieces or as a whole and the dust particles hold together well. The crust is thicker at places where the dust was more loosely packed, because the sputtering action goes deeper there.

3. The crust, when sectioned, has a fibrous structure, covered with needles and spires which are aligned in the direction of the ion bombardment. No difference exists between the behavior of Fe and Mo powder. This excludes the possibility that any melting effects are involved in the crust formation. In fact, the surface barely reaches the temperature of melting lead, as an experiment with lead dust showed.

c. Experiments With Compound and Insulating Powders

With insulators, a difficulty arises in maintaining an electric field to accelerate the ions towards the surface because of the charge which accumulates at the surface. Recently, a method employing radio-frequency fields was developed[7] to solve this problem. Bombardment

and sputtering are accomplished in a low-pressure, dc plasma by applying a high-frequency voltage to a metal electrode which is covered with the insulator material to be sputtered. A convenient frequency for this operation lies in the 1- to 10-mc range. The target in our experiments consisted of a quartz dish (with a metal bottom as the electrode) filled with a 2-mm thick layer of the powder to be sputtered. From the thickness of the dark ion sheath which covers the target, one can estimate that the maximum bombarding ion energy (which varies, of course, periodically between zero and the maximal value) was of the order of 500 ev at the observed 5 ma/cm^2 current density. Materials studied thus far include Al_2O_3, CuO, Cu_2O, FeO, Fe_2O_3, and various rock powders. The results can be summarized as follows:

1. The surface of many materials, after sufficient bombardment ($>$ 100 $coul/cm^2$), becomes covered with a brittle crust in which the individual dust particles become cemented together by sputtered atoms. Figure 7, for instance, shows that in the case of powdered basalt, a whole cemented surface crust can be lifted from the

dish. In Al_2O_3 only very little or very fragile crusting is observed. The crust is thicker in more loosely packed places or materials.

2. The surface layer of many compounds becomes enriched with metal atoms. Black CuO is first converted into red Cu_2O before becoming covered with a very porous Cu layer. The red Fe_2O_3 converts into Fe_3O_4, then to ferromagnetic FeO, and finally Fe metal traces appear on the surface. The reduction to a composition richer in metal and the formation of a "metal black" causes a darkening of the surface in most cases. Obviously, in the process of breaking up molecules under the bombardment and of sputtering atoms back and forth, oxygen atoms are more likely to escape from the surface than metal atoms.

3. As previously noted for metal powders, whenever a crust is formed it has a fibrous structure with closely spaced needles and spires and deep small holes all aligned in the direction of the ion bombardment. The predominance of microscopically very steep walls is evidenced by the fact that the surface looks rather dark when viewed in isotropic light, but becomes shiny when illuminated and viewed from the same oblique direction.

d. Experiments in Hydrogen Plasmas

The Hg-bombardment experiments described so far give an enhanced picture of the physical sputtering effects such as arise in the solar wind from He ions or α-particles. In the case of hydrogen ions, chemical effects may become superimposed and, therefore, as a next step to closer solar-wind simulation, similar powder-bombarding experiments were performed in a hydrogen discharge. In this case, the plasma was excited with high-frequency fields. The operating data were as follows: Hydrogen gas pressure controlled with a Pd leak and a pump throttle: 10^{-2} torr. Background impurity pressure in bakeable tube: 10^{-6} torr. Excitation of hydrogen plasma: 50-mc, 1-kw transmitter, inductively coupled by a tuned external ribbon wrapped around the tube. Sputtering of target: 2.5 mc (as in dc Hg plasma); bombarding ion current density, 2 ma/cm^2; maximum bombarding ion energy, 800 volts. In this discharge, one has an undetermined ratio of H^+, H_2^+, and H_3^+ ions. With the sputtering yields about 2 orders of magnitude lower than in Hg, one needs correspondingly longer sputtering times for obtaining visible effects.

In most experiments the bombardment amounted to) 100 coul/cm^2. Although chemical reactions between oxygen and hydrogen (with water molecule formation) may now become superimposed on physical sputtering; it turns out that the visible effects, with respect to crusting, reduction of oxides, darkening, etc., are very similar to those found for Hg-ion bombardment. Figure 8, for instance, shows pieces of the crust in cross section formed on Cu_2O powder. The thickness of this crust was approximately 0.2 mm. Figure 9 shows an oblique view of the same surface.

III. CONCLUSIONS

With respect to the lunar surface, the following conclusions can be drawn:

1. Sputtering by the solar wind must have caused some leveling and smoothing of surface features. The rate of this leveling is probably somewhat larger than the sputtering rate. We estimate that a narrow surface protrusion, 50 cm in height, could be completely leveled within the lifetime of the Moon.

2. Loose dust particles must have become somewhat crusted together under solar-wind conditions. With micrometeorites stirring up and turning the lunar surface material over continuously, one can assume that the crusting is not confined to the outermost surface layer but that over the millenia a very porous layer of brittle material with very low density has been built up. In this connection Öpik's[8] estimate that a complete turnover of the upper 1-cm layer by the action of micrometeorites would take place in about 10^4 years is of interest. We estimate that the layer in which solar-wind sputtering played an important part is probably several decimeters thick.

3. Oxides and other compounds became enriched with metal atoms. Such a possibility was recently discussed by Buettner[9] in connection with certain discrepancies in the electrical conductivity of the lunar surface. The metal-atom enrichment is partly responsible for the observed darkening of our bombarded samples. In the process of the reduction of oxides with hydrogen ions, water molecules may have been formed; some of these may have been trapped below the surface.

4. In our experiments, the surface crust assumes a fibrous structure with closely spaced needles and spires and deep small holes all aligned in the direction of bombardment. At the Moon, the conditions are different because the bombardment sweeps the surface over a range of angles. This should cause the surface to become more complex and irregular, but it probably would not change its basic character. This layer is probably not contradictory to the "fairy castle" structure proposed by Hapke[10] or the "skeletal fuzz" proposed by Warren[11] for explaining the photometric properties of the lunar surface.

5. Heavy metal atoms are favored for being retained and enriched for two reasons: The ejection velocities of heavy atoms are lower than those of light atoms and a higher proportion of these will fall back to the Moon. Heavier atoms, furthermore, have lower sputtering yields than light ones under light-ion bombardment on account of the poorer energy transfer.

LIST OF REFERENCES

1. G. K. Wehner, C. E. KenKnight, D. L. Rosenberg, "Sputtering Rates Under Solar-Wind Bombardment", Planetary and Space Science, accepted for publication.
2. L. Reiffel, Nature 185, 821 (1960).
3. E. J. Öpik, Planetary Space Science 9, 211 (1962).
4. G. K. Wehner, J. Appl. Phys. 29, 217 (1958).
5. G. K. Wehner, "Advances in Electronics and Electron Physics", 7, 239 (1955).
6. G. K. Wehner, J. Appl. Phys. 30, 1762 (1959).
7. G. S. Anderson, Wm. N. Mayer, G. K. Wehner, J. Appl. Phys. 33, 2991 (1962).
8. E. J. Öpik, Progress in the Astronautical Sciences, Vol. 1, North Holland Publ. Co., Amsterdam, p. 219 (1962).
9. K. J. K. Buettner, Planetary Space Science 11, 135 (1963).
10. B. W. Hapke, Proc. Lunar Surface Materials Conference. Boston, May 1963. To be published.
11. C. R. Warren, Science 140, 188 (1963).

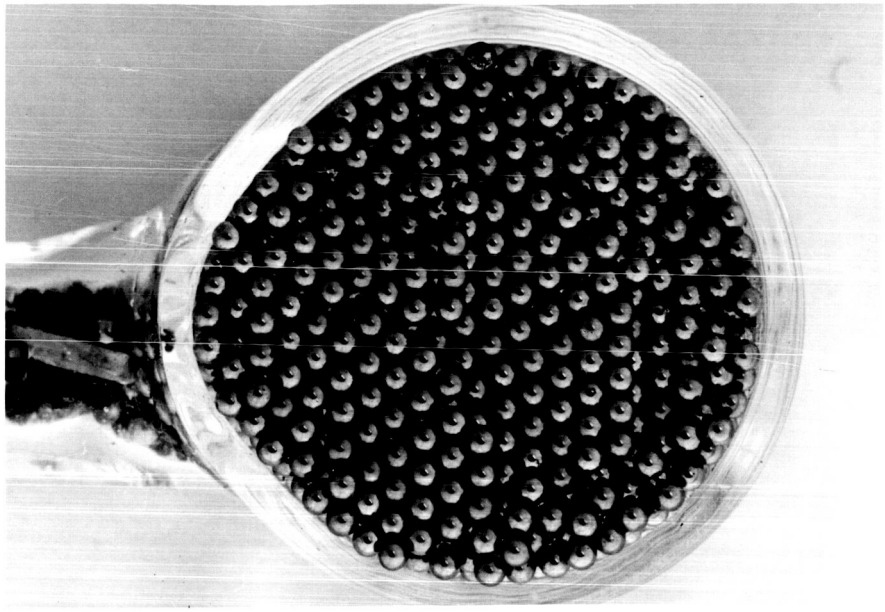

Fig. 1 Assembly of steel balls before sputtering.

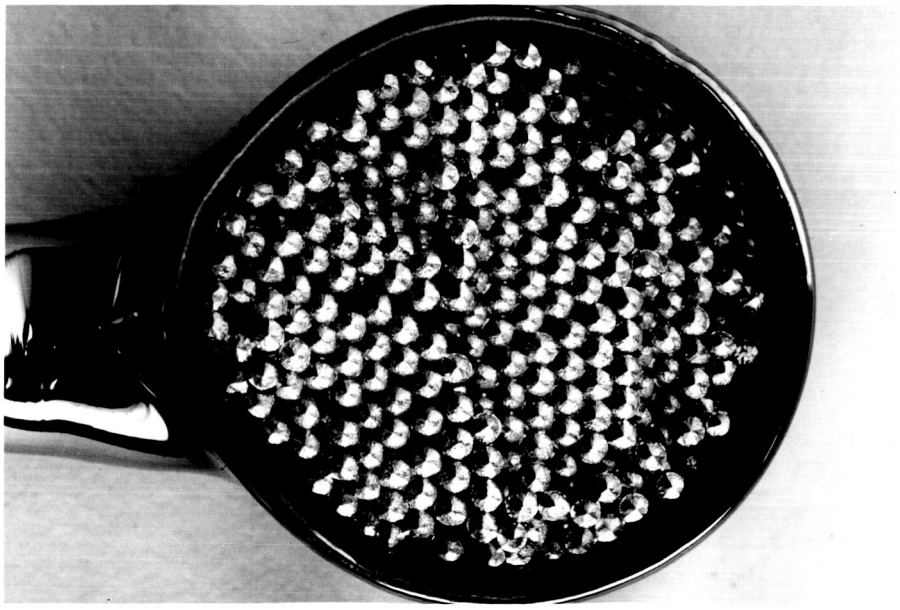

Fig. 2 Same target after 16 hours of sputtering by 500 ev Hg^+ ions at ~10 ma/cm^2 current density.

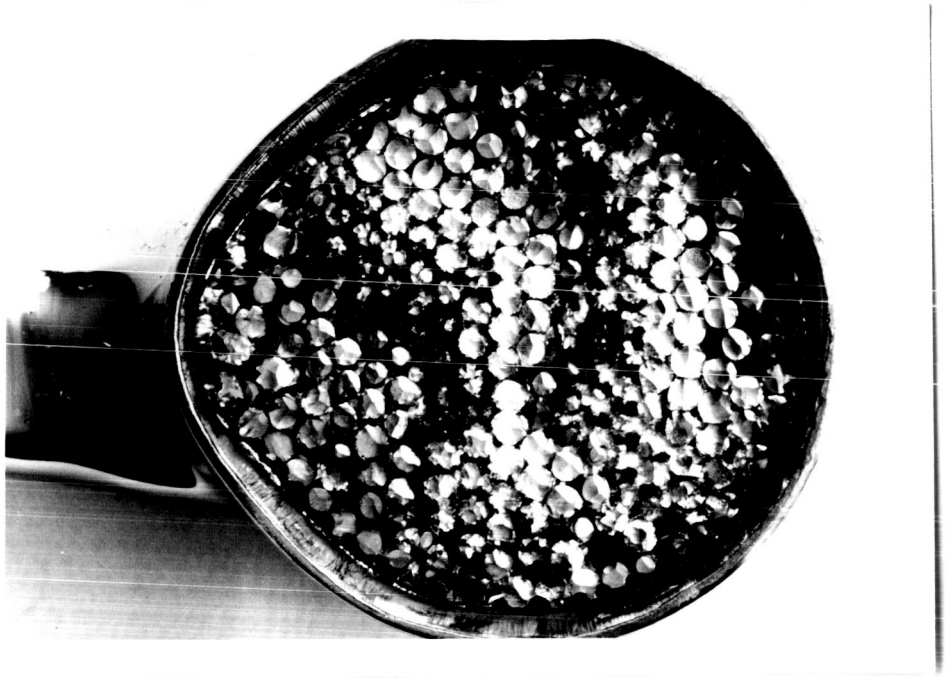

Fig. 3 Same target after 120 hours of sputtering under same conditions: Equivalent to 2.5×10^8 years of solar-wind sputtering at the lunar surface.

Fig. 4 Side view of same target as in Fig. 3.

Fig. 5 Second layer spheres sputtered only in places where top layer of spheres leaves open spaces.

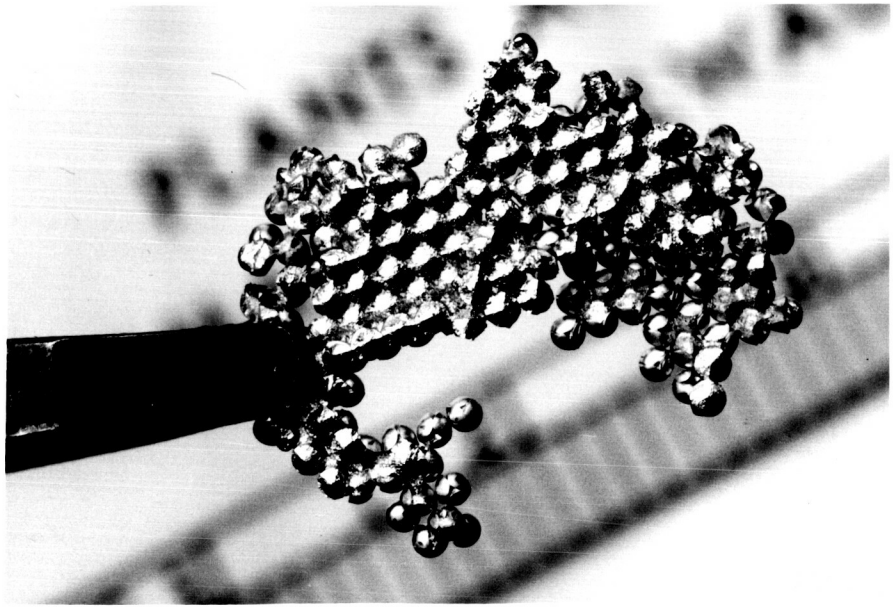

Fig. 6 Assembly of cemented top layers of spheres lifted from target shown in Fig. 3.

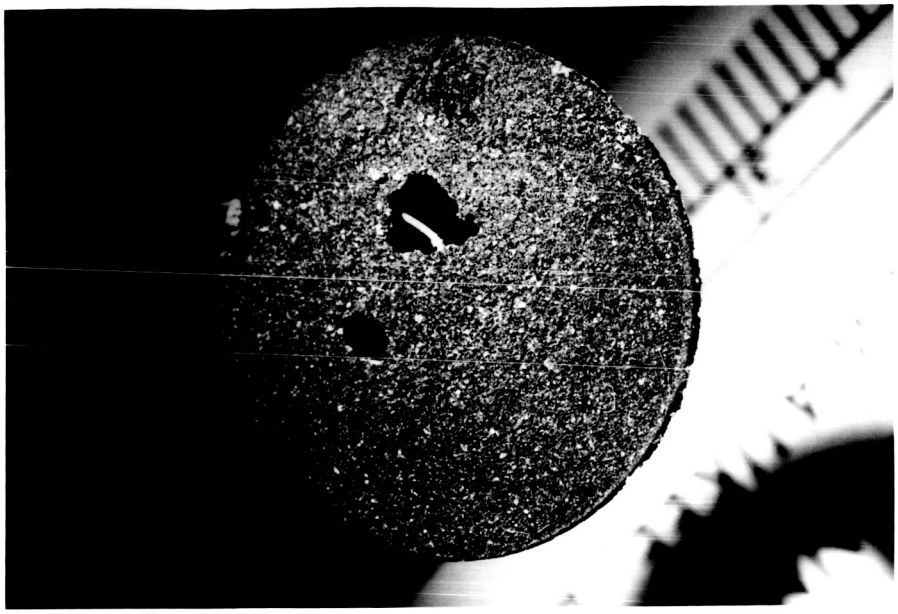

Fig. 7 Self-supporting surface crust lifted from target of powdered basalt after Hg^+ ion bombardment equivalent to 1.5×10^8 years of solar-wind bombardment.

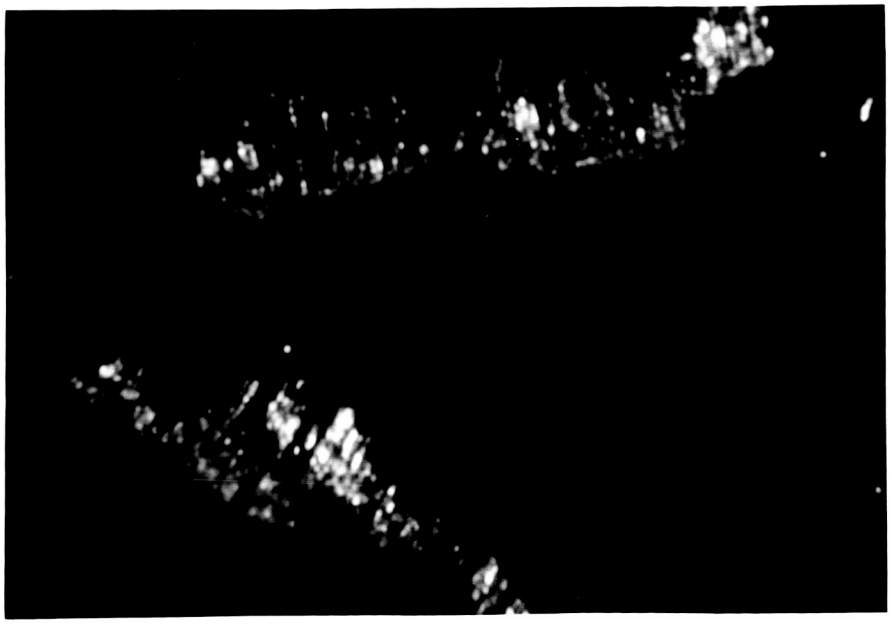

Fig. 8 Cross section view of pieces of crust formed on Cu_2O after bombardment with hydrogen ions equivalent to roughly 10^6 years of solar-wind action.

Fig. 9 Oblique view of same Cu_2O surface crust as in Fig. 8. (350x)